



MNLS Performance Analysis:

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EXECUTIVE SUMMARY

In this report, a detailed analysis of the Mobile-Assisted Network Location System (MNLS) performance is presented. MNLS represents a family of techniques designed to locate wireless IS-136/54 TDMA handsets, as required under the Federal Communications Commission (FCC) 94-102 mandate for wireless E911 location services. The MNLS technique described in this report is based on proprietary U.S. Wireless Corporation location pattern matching technology (LPM). Both theoretical (model-based) and empirical field test performance analyses are presented.

The theoretical analysis presented herein utilizes established propagation models and is developed for both ideal and actual carrier market conditions. Two model classes are considered, including the log-normal shadowing model and a CRC-based model. The CRC model is computed for two TDMA cellular markets including Oakland, CA and San Ramon, CA, representing an urban and suburban environment, respectively. For both markets, the models incorporate detailed carrier network data (such as cell site locations, antenna models, etc.) as well as terrain and clutter data. Simulation analysis for both the log-normal and CRC models predict that an MNLS system based on LPM technology would be capable of achieving performance better than 250m for 67% of the location fixes and better than 750m for 95% of the cases, under nominal operating conditions. A variety of special test cases are also considered which reveal the expected performance impact of variations in particular MNLS and Mobile-Assisted Handoff (MAHO) data parameters. The strongest parameter influences are predicted for changes in the MAHO time averaging interval (pre-processing of the MAHO data by averaging consecutive samples), the degree of correlation between pairs of channel measurements, and the number of channels in the MAHO neighbor list.

Empirical field test performance results are presented for MNLS testing conducted in the San Ramon and Oakland, CA test regions over a six-day period. Performance is evaluated for the identical test regions as were modeled in the theoretical analysis, to facilitate comparison and to establish the validity of the selected propagation models. MAHO data measurements were collected using two Ericsson TEMS Investigation TDMA 800/1900 air interface test tools and three unique TDMA handset models. A set of predetermined drive routes and stationary points were specified to provide comprehensive coverage and representative measurements of the conditions and operating environments expected within the designated test areas. Routes were typically repeated 4-6 times while systematically varying such parameters as the handset model, mobile speeds, antenna polarization, and time of day. A total of 390,362 MAHO data measurements were collected in Oakland, CA and 264,262 samples collected in the San Ramon, CA test region.

The statistical fluctuations of the MAHO data measurements are characterized in terms of two metrics - the Absolute Power Metric (APM) and Pairwise Power Difference Metric (PPDM), for the complete data sets collected in each market. The average standard deviation of the absolute power fluctuations within a 50m bin was found to be 9.66dB and 9.17dB for the Oakland and San Ramon markets, respectively. Similarly, the fluctuations of the pairwise measurements were found to be significantly more robust and less variable, exhibiting values of 4.36dB and 4.21dB for the Oakland and San Ramon markets, respectively.

The overall MNLS performance was measured and characterized in both test markets and was found to be in strong agreement with that which was predicted by the CRC model simulations. In the Oakland field test, the system achieved an overall MNLS accuracy of 183m for 67% of the location fixes, and 629m for 95% of the cases. For the San Ramon test region, the MNLS system achieved an overall accuracy of 214m for 67% of the location fixes, and 544m for 95% of the cases. The influence of variations in key MNLS system and MAHO data parameters were selectively isolated and evaluated, revealing trends similar to those predicted by the performance modeling and simulation analysis. In particular, variations in the handset model and handset orientation were found to have little impact on MNLS accuracy performance.

1 INTRODUCTION

1.1 OVERVIEW

In this report, a detailed analysis of Mobile-Assisted Network Location System (MNLS) performance capabilities is presented. MNLS represents a family of techniques designed to locate wireless IS-136/54 TDMA handsets, as required under the Federal Communications Commission (FCC) 94-102 mandate for wireless E911 location services. The MNLS technique described in this report is based on U.S. Wireless Corporation location pattern matching technology (LPM).

The purpose of this report is to provide both theoretical and empirical performance analyses to establish the expected performance capabilities of MNLS, and to characterize the performance impacts of specific system and environmental parameters. Towards this end, two studies are reported:

1. *MNLS Simulation Performance Analysis* – MNLS performance is characterized through computer simulation for two classes of RF propagation models including an ideal log-normal shadowing model and a more complex CRC model, developed by the Communications Research Center of Canada. The latter model incorporates existing carrier network data (cell site locations, antenna types, etc.) as well as detailed terrain and clutter databases for the San Ramon and Oakland, CA test regions.
2. *Field Test Performance Analysis* – The results of two MNLS field trials are presented for the San Ramon and Oakland, CA test areas. Over 650,000 MAHO samples were collected and analyzed under a variety of controlled test conditions.

1.2 DEFINITIONS, ACRONYMS & ABBREVIATIONS

Table 1: Definitions, Acronyms and Abbreviations

APM	Absolute Power Metric
Bin	A square geographic area representing the resolution of the calibration data (also referred to as a "grid").
CRC	Communications Research Center of Canada
LPM	Location Pattern Matching
MAHO	Mobile-Assisted Hand-Off
MNLS	Mobile-Assisted Network Location System
Neighbor List	For each serving channel, there is a designated neighbor list specifying the list of neighboring channels whose power is to be estimated for each MAHO data measurement.
Pass	A single data collection drive test passing through a bin area, while collecting with a single handset.
PPDM	Pairwise Power Difference Metric
TDMA	Time Division Multiple Access
TEMS Investigation	Air interface test equipment by Ericsson.
USWC	U.S. Wireless Corporation

1.3 REPORT ORGANIZATION

The remainder of this report is organized as follows. The MNLS simulation performance analysis is first described in Section 2. In Section 3 the complete field test results are presented for both the San Ramon and Oakland field trials. Finally, conclusions for the analyses are summarized in Section 4.

2 MNLS SIMULATION PERFORMANCE ANALYSIS

In this section, the theoretical performance of MNLS is modeled and evaluated by computer simulation. The purpose of this analysis is to gain insight into the performance potential of MNLS based on LPM technology, and to characterize the influence of specific propagation, environmental, system and algorithm parameters.

Two types of propagation models are employed in this analysis. The first is a standard log-normal shadowing model representing a relatively simple, ideal propagation environment. The second is a more complex propagation model computed specifically for two markets – San Ramon, CA and Oakland, CA. These latter models were developed using commercial RF propagation modeling tools and incorporating detailed carrier network data (cell site locations, antenna models, frequency plans, etc.) as well as detailed clutter and terrain data for each market. In Section 3 of this report, live field test results are presented for each of these markets, for comparison.

2.1 LOG-NORMAL SHADOWING MODEL

2.1.1 Model Description

The first propagation model used in the performance evaluation is an empirical log-normal shadowing model. A mathematical description of the propagation model is given by

$$P = P_0 - 10\gamma \log(r / r_0) + X,$$

where P_0 is the free-space propagation power, r is the range, and X is an additive zero-mean Gaussian noise component. The parameters γ and r_0 are selected based on the desired operating environment to be modeled. For this analysis, $\gamma = 3.5$ and $r_0 = 100\text{m}$ were selected to represent an urban / hilly environment.

The noisy MAHO data measurements were derived directly from the propagation model. The noise component was generated as an additive zero-mean Gaussian noise random variable, using a standard deviation of 9dB¹. Correlated slow fading was modeled by including a non-zero correlation coefficient for each pair of channel power measurements. The value of the

¹ The value of 9dB was selected for consistency with analyses described later in this report, and was based on field measurements made in the Oakland and San Ramon, CA test regions.

correlation coefficient was selected to yield a desired pairwise power difference standard deviation, typically in the range of 2-6dB².

The calibration tables were built from multiple “passes” of randomly generated (noisy) samples of MAHO data. In this manner, the calibration tables were not purely theoretical and were representative of the types of tables that would be generated in practice.

2.1.2 Simulation Analysis

For the performance analysis, a total of 25 cell sites were modeled as being deployed on a 5 x 5 uniform grid. For each performance test, a set of model parameters was specified. All parameters remained fixed except for the specific parameter under test. Three key MNLS algorithm parameters were defined as follows:

- *Calibration Bin Size* – specifies the size of the calibration bins. Bins are small, square geographic coverage areas that are represented by a single calibration point. Typical values for the length of a bin are 25m, 50m, 75m, and 100m.
- *Calibration Density* – specifies the number of “passes” used to create the calibration table. A “pass” is modeled as a single data collection drive test passing through a bin area, while collecting with a single handset. Typical values range from 3 to 6 passes.
- *MAHO Averaging Time* – the period of time over which the raw MAHO data measurements are collected and averaged, prior to applying the MNLS algorithm. Typical values include 1, 3, 5, and 7 seconds.

Unless otherwise stated, the default simulation parameters used in the analysis were as follows:

- *Cell Site Grid:* 2km (pairwise separations from 2 - 14km)
- *Calibration Bin Size:* 100m
- *Number of Neighbors:* 6
- *MAHO Time Averaging:* 5 seconds
- *Calibration Density:* 4 passes
- *Pairwise Power Difference Standard Deviation:* 6dB

For each test, a set of trials was simulated in which the parameter under test was systematically varied. For each of the trials, a unique calibration table was

² This value was selected based on field measurements made in Oakland and San Ramon, CA.

computed as well as a unique MAHO data test set covering all calibration bins. Location estimates were then computed for each test point using the MNLS method based on LPM. Performance was then characterized statistically for the 67th and 95th percentiles.

2.1.3 Results

MAHO Time Averaging – the predicted performance of the MNLS system as a function of the MAHO time averaging interval is summarized in Table 2. Results based on an averaging time of 1 second (a single MAHO data measurement) did not achieve the desired performance goal of 250m for 67% and 750m for 95% of the fixes. However, increasing the averaging time to 3 or more seconds improved performance substantially, and was able to meet the accuracy goal.

Table 2: Predicted performance as a function of the MAHO time averaging interval.

MAHO TIME AVERAGING (s)	67% (m)	95% (m)	<250m (%)	<750m (%)
1	400	806.23	48.75	93.28
3	223.61	500	70	100
5	223.61	412.31	80	100
7	200	360.56	85	100

Pairwise Power Difference Standard Deviation – the performance impact of the standard deviation of the pairwise power difference is summarized in Table 3. As the standard deviation decreased from 6 to 2dB, the degree of correlation between pairwise power fluctuations increased and the MNLS LPM location accuracy improved.

Table 3: Predicted performance as a function of the pairwise power difference standard deviation.

PAIRWISE POWER STANDARD DEVIATION (dB)	67% (m)	95% (m)	<250m (%)	<750m (%)
2	100	223.61	95.94	100
4	141.42	316.23	89.06	100
6	200	360.56	85	100

Number of Neighbors – the predicted performance as a function of the number of neighbors in the MAHO channel list (including the serving cell) is provided in Table 4. For this simulation, the MAHO time averaging interval was reduced to 1 second, to better reveal the influence of the neighbor list size. For longer averaging times, the impact of varying numbers of neighbors was less pronounced. In general, adding additional neighbors improved performance, unless the neighbors become too distant to provide reliable data.

Table 4: Predicted performance as a function of the number of neighbors.

NUMBER OF NEIGHBORS	67% (m)	95% (m)	<250m (%)	<750m (%)
4	412.31	721.11	39.47	95.97
6	360.56	670.82	47.88	97.03
8	316.23	608.28	50.13	98.13

Number of Calibration Passes – as the number of passes used to generate the calibration table was increased, the calibration signatures became less noisy and began to converge. The performance of the system as a function of the number of calibration passes is presented in Table 5. Once again, the MAHO time averaging interval has been decreased to 1 second, to better illustrate the impact of increasing the number of calibration passes. The most significant improvement was noted for the 95th percentile results, with a less pronounced improvement in the 67th percentile statistics.

Table 5: Predicted performance as a function of the number of calibration passes.

NUMBER OF CALIBRATION PASSES	67% (m)	95% (m)	<250m (%)	<750m (%)
1	412.31	806.23	42.66	93.28
2	412.31	806.23	44.22	93.13
3	400	721.11	45.47	95.94
4	400	704.4	47.81	97.5

2.2 CRC MODEL

2.2.1 Model Description

The second model used in the simulation analysis was based on the CRC propagation model developed by the Communication Research Center of Canada. This model is one of a class of diffraction models that incorporates terrain and clutter data to better estimate field strengths in a rigorous manner. All modeling was performed using the deciBel Planner RF propagation modeling tools from Marconi Wireless, along with Vertical Mapper (a software tool for grid processing) and MapInfo as the GIS and rendering tool.

The propagation models were based on actual network data from the TDMA cellular deployments in the San Ramon and Oakland, CA test regions³. These models also incorporate terrain information based on USGS 75m resolution

³ Specific carrier network data and coverage region maps are presented in Section 3.2.1 and Section 3.3.1 of this report for the Oakland and San Ramon test regions, respectively.

data. In addition, 200m clutter data was used in both test regions including the following classes: Dry Open, Wet Open, Scrub Forest, Residential, Commercial & Industrial, Urban, and Water (for Oakland only).

Once the models were generated, a dense grid of predicted field strengths was computed for all potential neighbor list channels within the test region. Noisy MAHO samples were generated using an additive zero-mean Gaussian noise process, identical to that which was described for the log-normal shadowing analysis. Using this data, the MNLS LPM technique was applied in a manner identical to that used in the previous section.

2.2.2 San Ramon, CA Model

The modeled best-server received power for the San Ramon, CA test region is shown in Figure 1. The number of predicted neighbor list channels that could be received by a mobile with a power greater than -113dBm is shown in Figure 2. The performance analysis permitted contributions from up to 20 sites in the test region.

Predicted performance results are summarized in Table 6 - Table 11, for a variety of test parameters. Unless otherwise stated, the default test parameters for this analysis were as follows:

- *Bin Size:* 100m
- *Number of Neighbors:* 6
- *MAHO Time Averaging:* 3 seconds
- *Calibration Density:* 4 passes
- *Pairwise Power Difference Standard Deviation:* 6dB

Note that in this case, a short MAHO time averaging period was used. This short period degrades overall performance slightly, but serves to highlight the influence of the other parameters under test. When a MAHO averaging time of 7 seconds was employed, the nominal MNLS system performance predicted for the test region was 174m for 67% of the location fixes, and 717m for 95% of the cases.

Table 6: Nominal predicted performance for the San Ramon test region, with 7-second MAHO measurement time averaging.

67% (m)	95% (m)	<250m (%)	<750m (%)
174.16	717.39	78.46	95.55

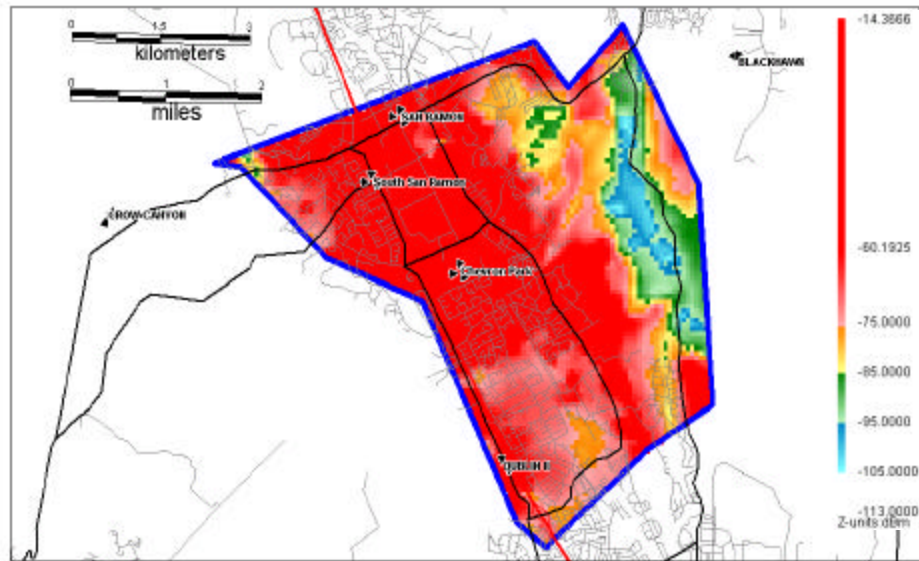


Figure 1: Modeled best server received power (dBm) for San Ramon, CA.

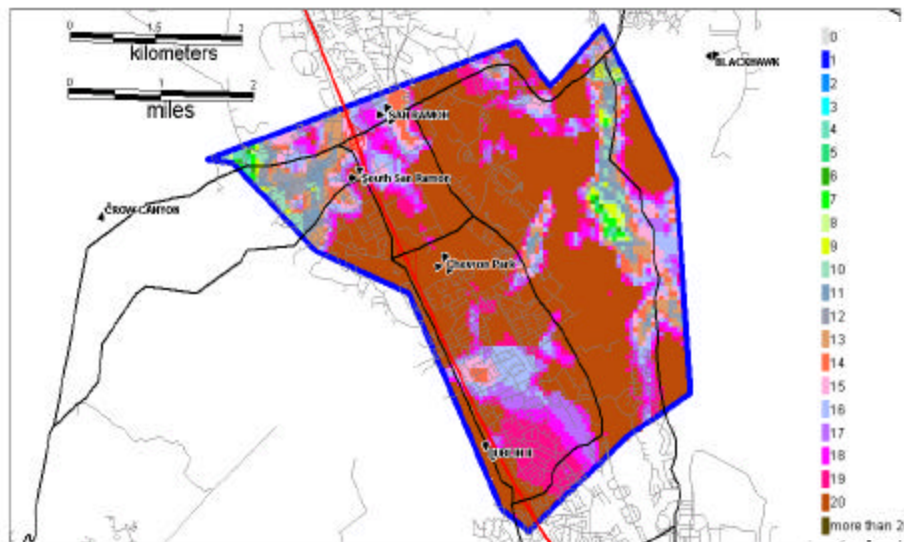


Figure 2: Modeled number of sites with received power > -113 dBm, San Ramon, CA.

Table 7: Predicted performance as a function of the MAHO time averaging interval.

MAHO TIME AVERAGING (s)	67% (m)	95% (m)	<250m (%)	<750m (%)
1	451.17	1951.9	47.96	82.15
3	270.81	1099.6	64.31	90.98
5	221.98	843.8	71.7	94.05
7	174.16	717.39	78.46	95.55

Table 8: Predicted performance as a function of the pairwise power difference standard deviation.

PAIRWISE POWER STANDARD DEVIATION (dB)	67% (m)	95% (m)	<250m (%)	<750m (%)
6	270.81	1099.6	64.31	90.98
4	212.22	770.55	72.7	94.68
2	175.65	638.2	78.65	95.74

Table 9: Predicted performance as a function of the number of neighbors.

NUMBER OF NEIGHBORS	67% (m)	95% (m)	<250m (%)	<750m (%)
4	453.22	1974.17	47.21	80.96
5	351.52	1723.86	56.67	85.85
6	270.81	1099.6	64.31	90.98
7	224.72	930.86	71.45	93.68
8	190.62	656.83	77.14	95.8

Table 10: Predicted performance as a function of the calibration bin size.

CALIBRATION BIN SIZE (m)	67% (m)	95% (m)	<250m (%)	<750m (%)
25	255.57	1111.94	66.69	91.73
50	253.37	1230.86	66.5	90.8
100	270.81	1099.6	64.31	90.98

Table 11: Predicted performance as a function of the number of calibration passes.

NUMBER OF CALIBRATION PASSES	67% (m)	95% (m)	<250m (%)	<750m (%)
2	274.03	1239.88	63.93	91.48
4	270.81	1099.6	64.31	90.98

Based on the parametric analyses, the following general performance trends are noted:

- *MAHO Averaging Time* – MNLS performance improves as the MAHO averaging time is increased from 1 to 7 seconds.
- *Pairwise Channel Correlation* - As the pairwise power difference standard deviation decreases (implying the fluctuations between pairs of channel power measurements become more correlated) the MNLS performance improves.
- *Neighbor List Size* - As the number of channel neighbors increases, the MNLS performance improves. The most dramatic improvement is seen for the 95th percentile statistics.
- *Calibration Bin Size* - Increasing the calibration bin size degraded the MNLS 67th percentile performance, while slightly improving the 95th percentile performance.
- *Calibration Passes* – Increasing the number of calibration passes from 2 to 4 had the most impact on the 95th percentile performance, while having minimal effect on the 67th percentile performance.

2.2.3 Oakland, CA Model

Similar to the San Ramon analysis, the modeled best-server received power for the Oakland, CA test region is shown in Figure 3. The number of predicted neighbors that could be received with a power greater than -113dBm is shown in Figure 4. Due to the density of sites in the Oakland market, the model predicts that virtual all of the allowed 20 neighbors would be received with sufficient power (hence, the uniform color in the test region).

Predicted performance results are summarized in Table 13 - Table 17, for the same set of test parameters as was employed in the San Ramon evaluation. Unless otherwise stated, the default test parameters for this analysis were as follows:

- *Bin Size:* 100m
- *Number of Neighbors:* 6
- *MAHO Time Averaging:* 3 seconds
- *Calibration Density:* 4 passes
- *Pairwise Power Difference Standard Deviation:* 6dB

Again, a short MAHO time average interval has been selected to slightly degrade overall performance, in order to highlight the influence of the

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parameters under test. The nominal MNLS system performance predicted for the test region was 141m for 67% of the location fixes, and 482m for 95% of the cases.

Table 12: Nominal predicted performance for the Oakland test region.

67% (m)	95% (m)	<250m (%)	<750m (%)
141.24	482.89	84.54	98.57

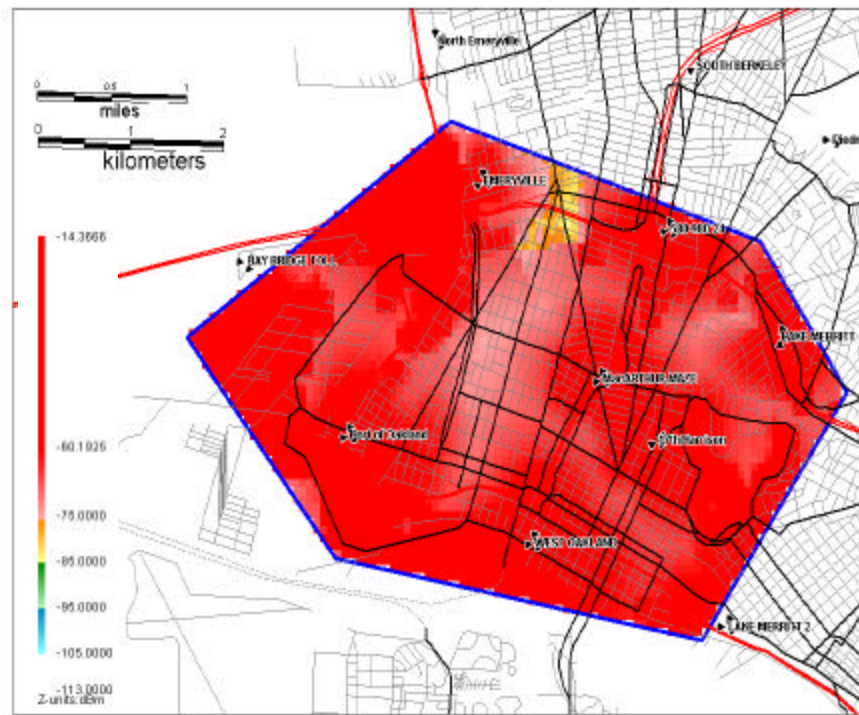


Figure 3: Modeled best server received power (dBm) for Oakland, CA.

Table 15: Predicted performance as a function of the number of neighbors.

NUMBER OF NEIGHBORS	67% (m)	95% (m)	<250m (%)	<750m (%)
4	218.05	695.73	70.14	95.70
5	177.97	604.74	77.22	97.89
6	141.24	482.89	84.54	98.57
7	96.60	443.81	86.73	99.40
8	48.92	364.20	88.69	99.55

Table 16: Predicted performance as a function of the calibration bin size.

CALIBRATION BIN SIZE (m)	67% (m)	95% (m)	<250m (%)	<750m (%)
25	158.09	506.16	81.37	98.27
50	149.72	499.83	81.60	97.59
100	141.24	482.89	84.54	98.57

Table 17: Predicted performance as a function of the number of calibration passes.

NUMBER OF CALIBRATION PASSES	67% (m)	95% (m)	<250m (%)	<750m (%)
2	155.78	488.71	81.00	98.42
4	141.24	482.89	84.54	98.57

In general, the performance trends observed for the San Ramon simulation are also present in the Oakland model. However, the impact of the parameter variations appears to be more pronounced in the Oakland case, indicating perhaps a greater sensitivity to these parameters.

2.3 SUMMARY

Both the ideal log-normal shadowing and CRC propagation models indicate that the LPM-based MNLS technique is able to achieve the MNLS performance goal of 250m for 67% and 750m for 95% of the cases, under nominal operating parameters.

The performance analyses for both models reflect common trends with respect to the influence of the system parameters under test. The strongest parameter influences were observed for the MAHO time averaging interval, the pairwise power difference standard deviation, and the number of neighbors. As the number of neighbors increased, the accuracy generally improved unless the contributing site became too distant to contribute reliable information. In simulations this generally occurred for neighbor lists beyond 8-10 sites.

The number of calibration passes used and the calibration bin size only weakly impacted performance beyond their nominal values. In practice, for non-theoretical propagation models (based on drive test calibration data), these parameters may have more impact.

3 FIELD TEST PERFORMANCE ANALYSIS

In this section, field test performance results are presented for MNLS testing conducted in the San Ramon and Oakland, CA test regions. Performance was evaluated for the identical test regions as were modeled and described in Section 2 of this report. Data was collected under a variety of controlled test conditions. This data was then processed to create various sets of calibration tables and drive test routes to parametrically evaluate the characteristics and accuracy of the MNLS system.

3.1 METHODOLOGY

The data collection and performance analysis procedures are described in the following three sections. Identical test equipment, collection procedures, and analysis techniques were used for both the San Ramon and Oakland, CA field tests.

3.1.1 Test Equipment

Two test vehicles were used to collect the MAHO data measurements. The equipment and configurations for each are shown in Figure 5 and Figure 6, respectively. The TEMS Investigation TDMA 800/1900 air interface test tool by Ericsson was the primary test equipment employed. The TEMS software was installed and operated on standard laptop computers.

A total of three mobile handsets were used for testing, each representing a unique phone model. Vehicle 1 was equipped with two mobile units including the Ericsson A1228di and KH668 models. This vehicle was configured to simultaneously collect data with both phones. Vehicle 2 used a single Ericsson T18 handset. A dashboard mount was used in both vehicles to permit testing of the handsets in various positions to evaluate effects due to antenna polarization. No modifications were made to the handset antennas, *i.e.*, no external or rooftop antennas were employed.

Each vehicle was equipped with a Garmin GPS unit connected to the laptop computer. The Garmin units were used to provide continuous GPS location fixes and timestamps, which were logged by the TEMS software.

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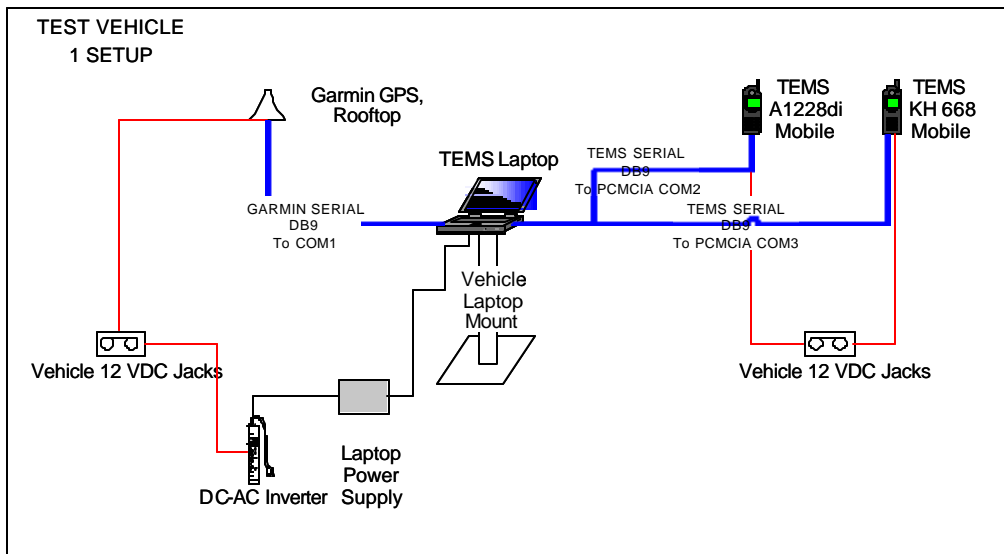


Figure 5: Test vehicle 1 configuration.

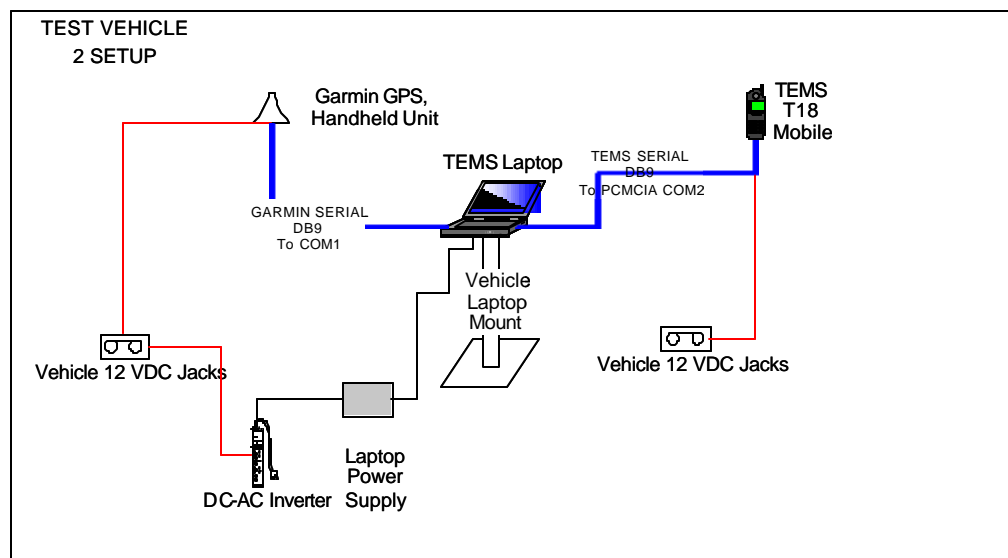


Figure 6: Test vehicle 2 configuration.

3.1.2 Collection Procedures

3.1.2.1 TEMS Investigation Configuration

For all data collections, the TEMS Investigation units were configured to collect both serving cell and neighboring cell measurements in the idle mode. All collections were performed in the 800MHz cellular band, and logged approximately once per second.

3.1.2.2 Drive Routes and Stationary Points

A set of predetermined drive routes and stationary points were established for both the San Ramon and Oakland, CA test regions. These routes and points were selected to provide comprehensive coverage and representative measurements of the conditions and operating environments expected within the designated test areas.

3.1.2.3 Data Collection

Each of the drive test routes and stationary points was repeated multiple times to permit parametric evaluation of the measurements for a variety of test conditions. Routes were typically repeated 4-6 times while systematically varying such parameters as the handset model, mobile speeds, antenna polarization, and time of day. Normal driving speeds were used during all mobile testing.

3.1.3 Analysis Procedures

3.1.3.1 MAHO Metrics

In order to characterize the statistical nature of the raw MAHO data measurements, two key metrics related to the signal power fluctuations were defined:

- 1) *Absolute Power Metric (APM)* – defined as the standard deviation of the absolute power measured for all channels in the neighbor list (including the designated serving channel).
- 2) *Pairwise Power Difference Metric (PPDM)* – defined as the standard deviation of the power difference measured for all possible pairs of channels in the neighbor list (including the serving channel).

Note that both metrics represent the standard deviation of a power measurement, and are specified in units of dB.

Both the APM and PPDM were computed within a set of square geographic areas, referred to as *bins*. For this analysis, the bin size (length of the side of the square) was varied from 50m – 100m. The metrics were computed for each individual bin, and then averaged for the entire test region.

All standard deviations were computed as centralized moments (mean value removed) in units of dB.

In order to accurately reflect the statistical variations of the metrics, the MAHO data set was first filtered to remove those samples lying near the edges of the allowable range of absolute power measurements. Recall that MAHO channel measurements are restricted to lie within the range of –51 to –113 dBm. Any measurements falling outside of this range are “clipped” and reported as the nearest boundary value. Therefore, those sets of data points whose mean power fell near either of these boundaries were eliminated from the analysis. In this manner, the APM and PPDM metrics were not biased or underestimated due to the clipping function. In addition, to ensure valid statistical significance, the metric statistics were only computed for those bins containing a sample set of 20 or more measurements.

3.1.3.2 Analysis Parameters

For the performance analysis, a number of key parameters have been defined for both the raw MAHO measurements and the MNLS processing algorithm. The MAHO measurement data is characterized in terms of three parameters:

- *Handset* – specifies which of the three handsets produced the MAHO measurement. Possible values include “1”, “2”, or “3”.
- *Mobility* – describes whether the handset was mobile or stationary at the time the MAHO measurement was collected. Possible values include “mobile” or “stationary”.
- *Antenna Polarization* – described the orientation of the handset antenna. Possible values include “vertical” or “horizontal”.

Similarly, the MNLS algorithm is parameterized according to the three parameters originally described in Section 2:

- *Calibration Bin Size* – Typical values include 25m, 50m, 75m, and 100m.
- *Calibration Density* – Typical values range from 3 to 6 (though up to 10 passes were recorded for one test).

- *MAHO Averaging Time* – Typical values include 1, 3, 5, and 7 seconds.

3.1.3.3 Test Set and Calibration Generation

For each test case evaluated a representative test set is selected from the complete data set, based on the desired parameter(s) under consideration. For example, when evaluating the influence of antenna polarization, two representative test sets are created – the first contains a subset of all samples obtained using a vertical antenna polarization, while the second set would contain similar data collected with horizontal polarization only. All of the remaining data (data not used in the test set) is made available for use in the calibration data, if required. In all test cases, the data that is contained in the test set is not incorporated in the MNLS calibration data. In this manner, the calibration data and test data are not unrealistically correlated.

In all test cases, the test set is selected to cover as much of the geographic test area as feasible, within the constraints of the desired test parameters. Due to practical test limitations, the complete data set cannot include all possible combinations of parameters in all test areas; therefore, certain test cases may be limited to only a subset of the coverage area or a subset of test parameters. As such, the performance of the MNLS technique for a specific test case may not match that of the overall (or nominal) system performance for the entire test region. This does not, however, negatively impact the ability to evaluate the *influence* of specific test parameters since it is the *relative* performance trends within a given test set that are of interest in this analysis.

3.1.3.4 MNLS LPM Algorithm

The MNLS technique evaluated in this analysis is a straightforward modification of the location pattern matching algorithms previously developed for use with the USWC RadioCamera™ system. No MAHO data pre-processing is performed other than the simple averaging over a predetermined time interval, typically in the 3-7 second range. In addition, no post-processing techniques have been applied in this analysis. In future analyses, performance will be characterized with additional pre- and post-processing, including Kalman tracking of consecutive MNLS location estimates and filtering of those estimates falling outside of the known serving cell coverage area.

3.1.3.5 Statistical Performance Analysis

For each test case, the statistical performance of MNLS is characterized in terms of the accuracy achieved (in meters) for the 67th and 95th percentiles. In addition, the percentage of location fixes falling within the proposed 250m and 750m performance goals is also presented.

3.2 OAKLAND, CA FIELD TEST RESULTS

3.2.1 Test Region and Wireless Network

The Oakland, CA test region is shown in Figure 7. The primary coverage area is approximately 8.5 square miles, and includes the urban downtown area. In addition to the primary coverage area, several additional highway routes (including the Bay Bridge) were collected beyond the test region boundaries. The test area includes a variety of terrain and environment types including urban, commercial, waterfront, highway and residential areas.

The TDMA carrier network in this region is operated in the 800MHz cellular band. A total of 26 carrier sites were found to be contributing as either serving cells or members of a neighbor list. Note that the large number of cells is due to the inclusion of those sites well outside of the coverage area serving as neighbors for sites within the coverage region, as well as the inclusion of sites providing service for the extended highway runs. All cell sites in the vicinity are shown in Figure 7. The pairwise separation distance between all sites serving this region is summarized in Table 18. In this case, site separations range from approximately 1km to 15km. A total of 64 unique frequency channels were observed within the test region, with 49 of these designated as the primary serving cell for some portion of the coverage area. Recall that due to the use of sectorization, the actual number of serving cell sites is much lower. The size of the neighbor list (total number of channels including the serving cell) ranged from 3 - 12 within the test region.

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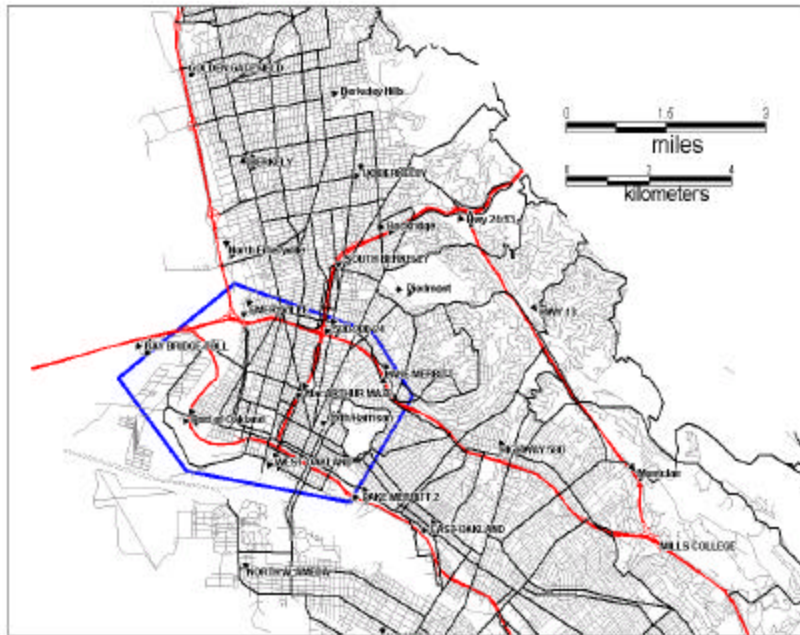


Figure 7: Oakland, CA field test region. Additional highways falling outside of the designated test region (including the Bay Bridge) were also included in testing.

Table 18: Pairwise site separation distance (km) for all carrier sites serving the Oakland, CA test region.

Name	Berkeley	E Oakland	Lake Merritt	N Emeryville	W Oakland	Golden Gate Field	Montclair	Piedmont	S Berkeley	Rockridge	High Street	N Alameda	Mills College	UC Berkeley	MacArthur Maze	Lake Merritt II	580 980 24	Berkeley Hills	Port of Oakland	Hwy 24/13	Emeryville	17th/Harrison	Alameda	Highway 580	Hwy 13	Bay Bridge Toll	
Berkeley	-	9.37	5.75	2.04	6.79	2.60	11.70	4.72	3.14	3.62	12.58	9.23	13.16	2.73	5.35	8.01	4.25	2.73	5.94	5.42	3.30	6.06	11.19	8.87	7.79	4.86	
E Oakland	-	-	3.71	8.00	4.07	11.96	5.17	5.47	6.47	6.94	3.21	4.58	5.55	8.20	4.36	1.83	5.12	10.14	6.32	7.07	6.63	3.52	2.69	2.45	5.58	8.08	
Lake Merritt	-	-	-	4.69	3.32	8.36	6.54	1.98	2.77	3.34	6.87	5.59	7.73	4.53	1.98	2.83	1.59	6.46	4.77	4.03	3.56	1.65	5.96	3.30	4.02	5.83	
N Emeryville	-	-	-	-	4.93	4.22	11.12	4.39	2.82	3.90	11.20	7.27	12.40	3.68	3.71	6.44	3.10	4.51	3.90	5.84	1.43	4.51	9.52	7.99	7.68	2.96	
W Oakland	-	-	-	-	-	9.14	8.79	5.04	4.90	6.00	6.92	2.57	9.50	6.85	1.73	2.24	3.34	8.53	2.25	7.21	3.51	1.66	4.75	5.45	7.26	4.11	
Golden Gate Field	-	-	-	-	-	-	14.20	7.24	5.72	5.99	15.17	11.45	15.70	4.84	7.84	10.54	6.84	3.72	7.91	7.56	5.64	8.60	13.69	11.46	10.13	6.36	
Montclair	-	-	-	-	-	-	-	6.98	8.59	8.22	5.25	9.76	1.75	9.48	8.28	6.70	8.06	11.21	10.87	7.05	10.09	7.57	7.20	3.37	4.32	12.28	
Piedmont	-	-	-	-	-	-	-	-	1.64	1.49	8.50	7.47	8.46	2.80	3.40	4.81	1.97	4.73	5.96	2.17	3.81	3.45	7.89	4.30	3.29	6.46	
S Berkeley	-	-	-	-	-	-	-	-	-	1.29	9.63	7.46	10.02	1.96	3.18	5.39	1.60	3.78	5.16	3.12	2.55	3.61	8.61	5.74	4.89	5.22	
Rockridge	-	-	-	-	-	-	-	-	-	-	9.99	8.53	9.78	1.32	4.28	6.15	2.67	3.24	6.44	1.94	3.84	4.56	9.30	5.76	4.17	6.48	
High Street	-	-	-	-	-	-	-	-	-	-	-	6.41	4.54	11.28	7.52	4.83	8.33	13.22	9.13	9.79	9.81	6.70	2.83	4.54	7.72	11.02	
N Alameda	-	-	-	-	-	-	-	-	-	-	-	-	10.04	9.41	4.28	3.29	5.88	11.09	3.70	9.61	5.93	4.02	3.65	6.74	9.23	5.66	
Mills College	-	-	-	-	-	-	-	-	-	-	-	-	-	11.06	9.28	7.29	9.30	12.85	11.69	8.73	11.27	8.50	6.99	4.43	6.03	13.26	
UC Berkeley	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.13	7.28	3.56	1.94	6.90	2.74	4.09	5.56	10.48	7.07	5.31	6.55	
MacArthur Maze	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.74	1.61	6.86	2.79	5.57	2.30	0.84	5.85	4.92	5.99	4.00	
Lake Merritt II	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.86	9.17	4.49	6.77	5.03	1.95	3.22	3.50	5.99	6.27	
580 980 24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.36	3.98	4.09	2.07	2.01	7.08	4.89	5.02	4.58	
Berkeley Hills	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8.22	4.21	5.39	7.38	12.38	8.98	6.94	7.46	
Port of Oakland	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8.06	2.84	3.34	6.79	7.50	8.77	1.99	
Hwy 24/13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.65	5.60	9.67	5.29	2.74	8.33
Emeryville	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.12	8.09	6.84	7.03	2.68	
17th/Harrison	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.13	4.19	5.63	4.76	
Alameda	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.08	8.26	8.76	
Highway 580	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.27	8.92	
Hwy 13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	9.61	
Bay Bridge Toll	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	

3.2.2 Data Collection

A composite of all drive test routes is shown in Figure 8. A total of 390,362 MAHO data measurements were collected and evaluated as part of the Oakland, CA field trial.

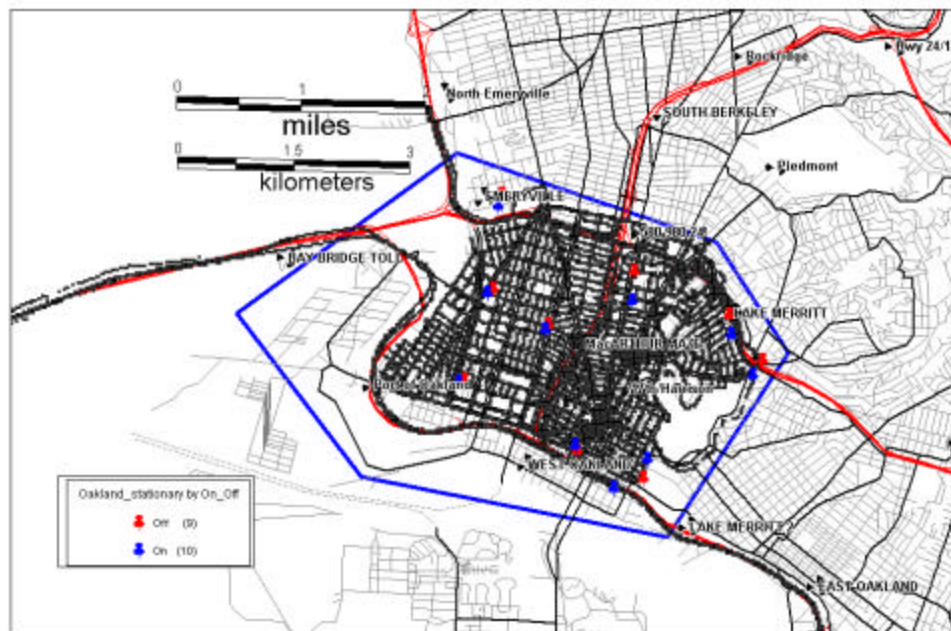


Figure 8: Oakland, CA data collection – composite of all drive test routes and stationary point collections.

3.2.3 MAHO APM and PPDM Results

The statistical fluctuations of the MAHO data measurements were characterized in terms of the APM and PPDM for the complete data set (over 390,000 samples). Recall that this data set included comprehensive geographic coverage and included the full range of handset, mobility, and polarization parameters. The specific analysis parameters were as follows:

- Bin Size: 50m
- Time Averaging: 1 second (1 sample)
- Antenna Polarization: Mixed
- Mobile vs. Stationary: Mixed
- Handset Model: Mixed (three)

The average value of the standard deviation of absolute power fluctuations was found to be 9.66dB, and exhibited a standard deviation of 4.07dB. As such the APM values were observed to vary significantly across bins within the coverage area. The fluctuations of the pairwise power differences were found to be much more stable, with an average PPDM value of 4.36dB and a standard deviation of 1.21dB. A map of the PPDM is shown in Figure 9 where it can be seen that the pairwise power differences are fairly uniform throughout the coverage area, with slightly higher variation in the urban downtown region and portions of the outlying highways. A summary of the APM and PPDM results is provided in Table 19.

The results obtained for the standard deviation of the absolute power are consistent with those predicted by standard propagation models under similar topography and clutter conditions^{4,5}. The pairwise power difference results are also as expected given the assumption of a correlated, slow-fading environment.

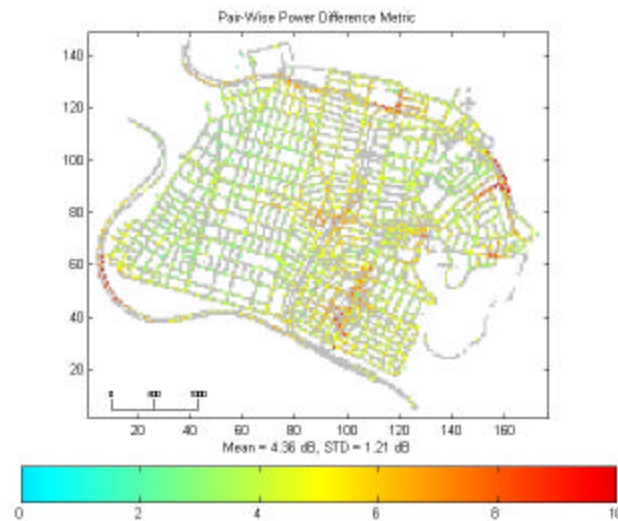


Figure 9: Pairwise power difference metric (PPDM) shown per bin in Oakland, CA.

⁴ European Digital Cellular Telecommunications System (Phase 2) Radio Network Planning Aspects, GSM 03.30, ETSI Technical Report ITR-103, p. 8, October 1993.

⁵ Mobile Communications Systems, Parson & Gardner, Blackie, London, pp. 93-94, 1989.

Table 19: Summary of MAHO power metrics for Oakland, CA.

METRIC	MEAN of METRIC	STANDARD DEV. of METRIC
Absolute Power Metric (APM)	9.66 dB	4.07 dB
Pairwise Power Difference Metric (PPDM)	4.36 dB	1.21 dB

3.2.4 MNLS Performance Results

The overall performance of the MNLS system in the Oakland, CA test region was first evaluated by creating a general test data set (over 80,000 randomly selected MAHO samples) representing the full range of MNLS and MAHO parameters. That is, samples representing all possible handsets, antenna polarizations, and mobility parameters were represented. The remaining data was then used to create a calibration table for the region. A summary of the overall MNLS performance obtained for the Oakland test region is provided in Table 20. The specific MNLS configuration parameters used in this evaluation are shown in Table 21. For the Oakland test region, the MNLS system achieved an overall accuracy of 183m for 67% of the location fixes, and 629m for 95% of the cases. The relative accuracy performance throughout the test region is shown in Figure 10 for each of the test points.

Table 20: Overall accuracy of the MNLS system in Oakland, CA.

# FIXES	67% (m)	95% (m)	<250m (%)	<750m (%)
80,028	183	629	76.8	96.8

Table 21: MNLS configuration parameters for overall performance analysis in Oakland, CA.

CAL BIN SIZE (m)	CAL DENSITY	MAHO AVG TIME (s)	ANTENNA POLARIZATION	MOBILITY	HANDSETS
50	4-6	7s	Mixed	Mixed	Mixed

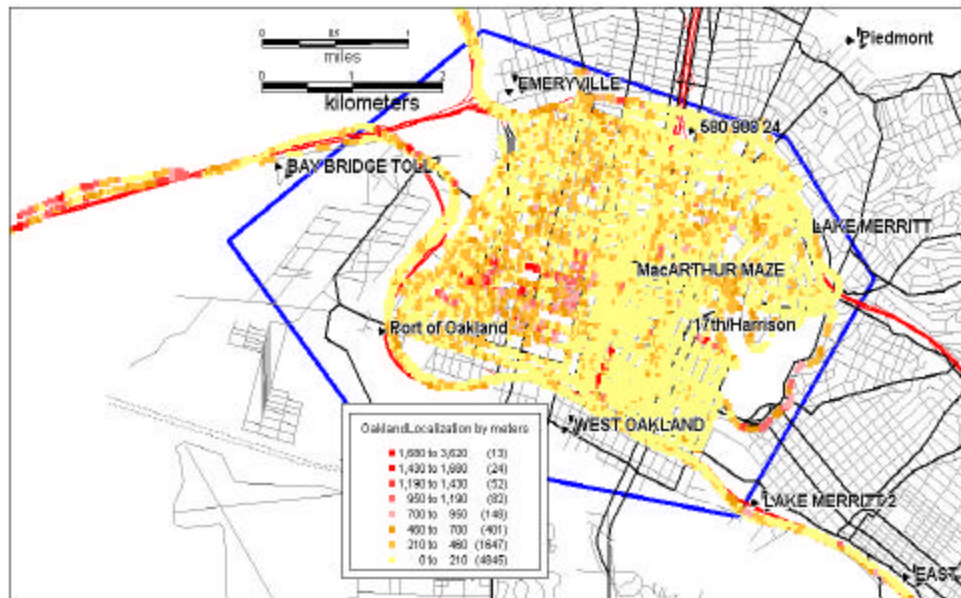


Figure 10: MNLS accuracy as a function of geographic location – Oakland, CA.

Additional testing was also performed to characterize the effects and impact of the various MNLS system parameters. Such analysis was conducted to better understand the system performance limitations and to establish guidelines for properly setting the MNLS calibration and operating parameters. For this series of analyses, two general types of test were conducted. The first tests involved reprocessing the overall test data set while varying the MNLS algorithm parameters. The second testing involved creating additional test data sets in which a specific MAHO parameter of interest was isolated for analysis. The results of both analyses are summarized in Table 22 - Table 25. For this analysis, unless otherwise stated, the default MNLS algorithm parameters are 5 seconds for MAHO time averaging (preprocessing), 50m-calibration bin size, and 4 or more calibration passes.

Table 22: Accuracy as a function of calibration bin size – Oakland, CA.

CALIBRATION BIN SIZE (m)	67% (m)	95% (m)	<250m (%)	<750m (%)
25	186	606	76.4	96.9
50	190	632	75.8	96.7
75	189	631	75.6	96.7
100	193	637	76.3	96.5

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Table 23: Accuracy as a function of calibration density – Oakland, CA.

CALIBRATION DENSITY (PASSES)	67% (m)	95% (m)	<250m (%)	<750m (%)
1	226	661	70.7	96.4
2	203	633	74.0	96.7
3	196	631	75.2	96.8
4	193	632	75.1	96.6

Table 24: Accuracy as a function of MAHO averaging time – Oakland, CA.

MAHO AVERAGING TIME (S)	67% (m)	95% (m)	<250m (%)	<750m (%)
1.0	204	646	74.0	96.3
3.0	193	633	75.5	96.6
5.0	190	632	75.8	96.7
7.0	183	629	76.8	96.8

Table 25: Accuracy as a function of the MAHO parameters - Oakland, CA. MAHO time averaging was set to 3 seconds for polarity testing.

TEST TYPE	67% (m)	95% (m)	<250m (%)	<750m (%)
Mobile	197	670	75.1	96.1
Stationary	132	539	80.1	97.5
Vertical Polarization	163	531	81.3	98.0
Horizontal Polarization	173	618	78.4	97.0
Handset 1	231	724	69.4	95.3
Handset 2	239	795	68.6	94.4

From these results, the following performance trends are noted:

- *Calibration Bin size* – increasing the calibration bin size from 25 – 100 meters degraded performance slightly, with a more substantial impact on the 95th percentile performance. In a built up area such as Oakland, this effect is likely due to the rapid change in clutter (buildings, etc.) within a relatively short spatial distance.
- *Calibration Density* – increasing the calibration density from 1 – 4 passes improved system accuracy by approximately 30m for both the 67th and 95th percentile performance metrics. Multiple calibration passes (or a single collection with multiple handsets) are necessary to ensure that the calibration has converged and captured a representative set of MAHO parameter variations.

- *MAHO Averaging Time* – preprocessing of the MAHO data by time-averaging the raw samples improved performance. Accuracy improved by approximately 20m as the averaging time increased from 1 second to 7 seconds. Further performance improvements through increased averaging time are likely to be bounded by the same phenomenon that degraded performance as the calibration bin size was increased. The introduced variations due to clutter changes as the mobile traverses through the environment are expected to become the dominant (and limiting) effect.
- *MAHO Parameters* – no significant performance differences were observed for changes in antenna polarization or for changes in the specific handset under test. MNLS performance for stationary handsets was better than that observed for mobile handsets in this environment. This result may be influenced by the degraded performance observed on the Bay Bridge – which would negatively impact the mobile results. Further analysis is required to more completely characterize performance as a function of mobility.

3.3 SAN RAMON, CA FIELD TEST RESULTS

3.3.1 Test Region and Wireless Network

The San Ramon, CA test region is shown in Figure 11. The total coverage area is approximately 14 square miles, and contains a mix of both residential and commercial development. The terrain is predominantly flat in the center of the coverage area with hilly sections near the coverage boundaries. Evaluation of the MAHO metrics was conducted throughout the entire test region, while MNLS performance testing was limited to the upper third of the test area (the remaining analysis is in progress).

The TDMA carrier network in this region is operated in the 800MHz cellular band. Based on drive test data analysis and propagation modeling, it was determined that 12 carrier sites are used in the test region as either serving cells or members of a neighbor list. All cell sites in the vicinity are shown in Figure 11. The pairwise separation distance between all sites serving this region is summarized in Table 26. Site separations range from approximately 1km to 16km. A total of 52 unique frequency channels were observed within the test region, with 24 of these designated as the primary serving cell for some portion of the coverage area. As was the case in the Oakland field test, the size of the neighbor list (total number of channels including the serving cell) ranged from 3 – 12 within the test region.

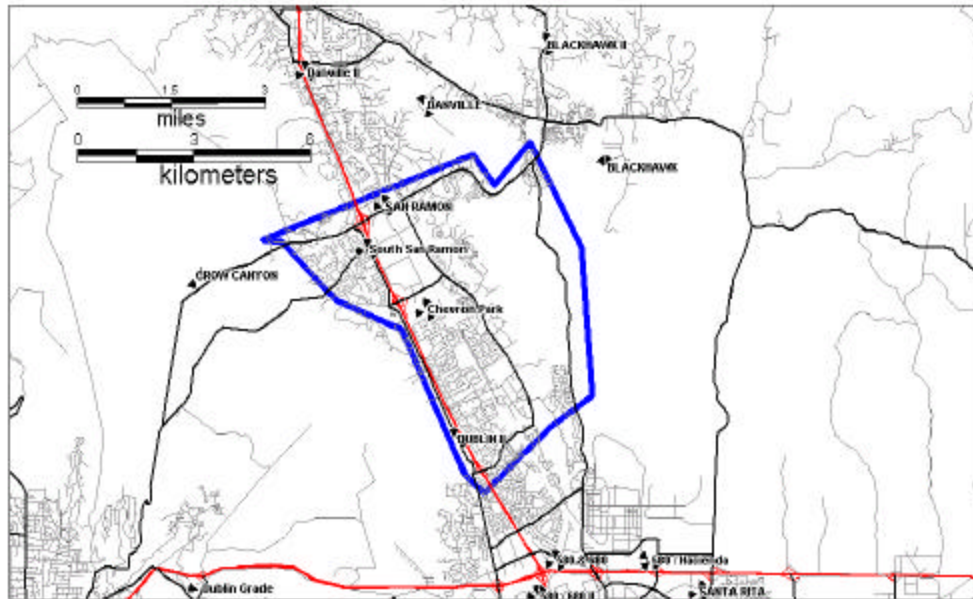


Figure 11: San Ramon, CA field test region.

Table 26: Pairwise site separation distance (km) for San Ramon, CA test region.

Name	DVCC	Dublin II	Santa Rita	580 and 680	San Ramon	Danville	Danville II	Chevron Park	N Pleasanton	Blackhawk	S San Ramon	580 680 II	580 Hacienda
Dublin II	-	-	7.232	3.872	5.879	8.034	9.608	3.212	6.163	7.597	5.080	4.330	5.788
Santa Rita	-	-	-	3.767	12.273	13.602	16.033	9.757	1.852	10.459	11.821	4.137	1.445
580 and 680	-	-	-	-	9.566	11.408	13.352	6.891	2.338	9.543	8.882	0.972	2.463
San Ramon	-	-	-	-	-	2.633	3.796	2.684	11.674	5.792	1.134	10.165	10.901
Danville	-	-	-	-	-	-	3.177	4.881	13.310	4.879	3.767	12.128	12.336
Danville II	-	-	-	-	-	-	-	6.461	15.470	8.055	4.543	13.925	14.677
Chevron Park	-	-	-	-	-	-	-	-	9.039	5.782	2.064	7.480	8.351
N Pleasanton	-	-	-	-	-	-	-	-	-	10.781	11.074	2.417	1.435
Blackhawk	-	-	-	-	-	-	-	-	-	-	6.469	10.468	9.498
S San Ramon	-	-	-	-	-	-	-	-	-	-	-	9.408	10.414
580 680 II	-	-	-	-	-	-	-	-	-	-	-	-	3.037
580 Hacienda	-	-	-	-	-	-	-	-	-	-	-	-	-

3.3.2 Data Collection

A composite of all drive test routes conducted for the San Ramon field trial is shown in Figure 12. A total of 264,262 MAHO data measurements were collected and evaluated.

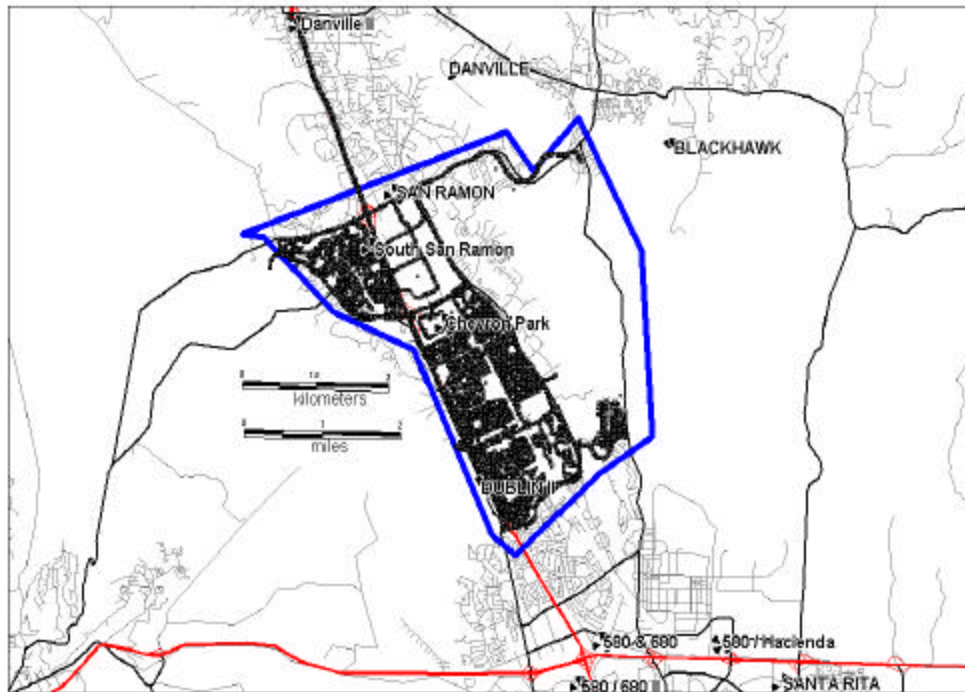


Figure 12: Composite of the data collection drive test routes – San Ramon, CA.

3.3.3 MAHO APM and PPDM Results

The statistical fluctuations of the MAHO data measurements were again characterized in terms of the APM and PPDM for the complete data set (over 260,000 samples). This data set included comprehensive geographic coverage and included the full range of handset, mobility, and polarization parameters. The specific analysis parameters were as follows:

- Bin Size: 50m
- Time Averaging: 1 second (1 sample)
- Antenna Polarization: Mixed
- Mobile vs. Stationary: Mixed
- Handset Model: Mixed (three)

The average value of the standard deviation of absolute power fluctuations was found to be 9.17dB, and exhibited a standard deviation of 4.00dB. These results are slightly lower than those observed in the Oakland, CA field trial. The fluctuations of the pairwise power differences were found to exhibit an average

PPDM value of 4.21dB and a standard deviation of 1.11dB – again, slightly lower than results obtained in Oakland, CA. A summary of the APM and PPDM results is provided in Table 27.

Table 27: Summary of the MAHO power metrics for San Ramon, CA.

METRIC	MEAN of METRIC	STANDARD DEV. of METRIC
Absolute Power Metric (APM)	9.17 dB	4.00 dB
Pairwise Power Difference Metric (PPDM)	4.21 dB	1.11 dB

3.3.4 MNLS Performance Results

Similar to the Oakland trial analysis, the overall performance of the MNLS system in the San Ramon, CA test region was first evaluated by creating a general test data set (over 55,000 randomly selected MAHO samples) representing the full range of MNLS and MAHO parameters including all possible handsets, antenna polarizations, and mobility parameters. The remaining data was again used to create a calibration table for the region. A summary of the overall MNLS performance obtained for the San Ramon test region is provided in Table 28. The specific MNLS configuration parameters used in this evaluation are shown in Table 29. For the San Ramon test region, the MNLS system achieved an overall accuracy of 214m for 67% of the location fixes, and 544m for 95% of the cases. The relative accuracy performance throughout the test region is shown in Figure 13 for each of the test points. As previously noted, additional San Ramon testing is in progress; therefore results are currently limited to a subset of the test region.

Table 28: Overall accuracy of the MNLS system in San Ramon, CA.

# FIXES	67% (m)	95% (m)	<250m (%)	<750m (%)
56,361	214	544	72.3	98.1

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Table 29: MNLS configuration parameters for overall performance analysis in San Ramon, CA.

CAL BIN SIZE (m)	CAL DENSITY	MAHO AVG TIME (s)	ANTENNA POLARIZATION	MOBILITY	HANDSETS
50	4-6	7s	Mixed	Mixed	Mixed

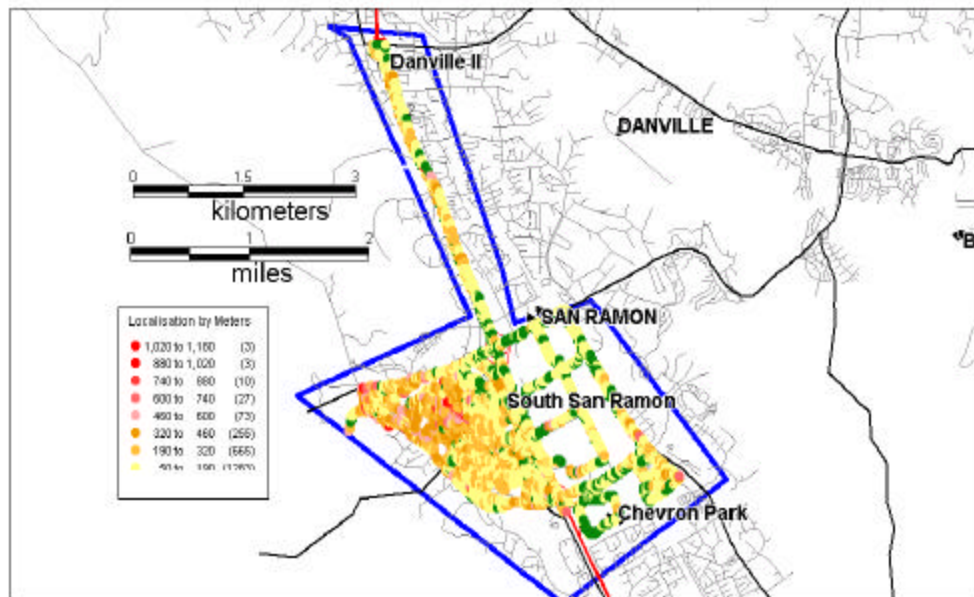


Figure 13: MNLS accuracy as a function of geographic location – San Ramon, CA.

Parametric testing was again performed to characterize the effects and impact of the various system parameters – including both the MNLS algorithm parameters and the MAHO parameters. The default analysis parameters, unless otherwise stated, were fixed at 5 seconds for MAHO time averaging (data preprocessing), 50m-calibration bin size, and 4 or more calibration passes. Performance results are summarized in Table 30 - Table 33.

Table 30: Accuracy as a function of calibration bin size – San Ramon, CA.

CALIBRATION BIN SIZE (m)	67% (m)	95% (m)	<250m (%)	<750m (%)
25	219	564	71.6	97.9
50	222	557	71.3	97.9
75	219	571	71.8	97.4
100	225	577	71.3	97.1

Table 31: Accuracy as a function of calibration density – San Ramon, CA.

CALIBRATION DENSITY (PASSES)	67% (m)	95% (m)	<250m (%)	<750m (%)
1	220	567	71.7	97.9
2	211	569	73.5	97.7
3	199	558	74.9	97.8

Table 32: Accuracy as a function of MAHO averaging time – San Ramon, CA.

MAHO AVERAGING TIME (S)	67% (m)	95% (m)	<250m (%)	<750m (%)
1.0	238	572	69.0	97.8
5.0	222	557	71.3	97.9
7.0	214	544	72.3	98.1

Table 33: Accuracy as a function of selected parameters - San Ramon, CA. MAHO time averaging set at 3 seconds.

TEST TYPE	67% (m)	95% (m)	<250m (%)	<750m (%)
Vertical Polarization	240	445	70.5	99.3
Horizontal Polarization	252	518	66.7	99.5
Handset 1	256	597	65.6	98.3
Handset 2	248	644	67.3	96.4

From these results, the following performance trends are observed:

- *Calibration Bin size* – increasing the calibration bin size from 25 – 100 meters again degraded performance slightly, but to a lesser extent than that observed in Oakland, CA. This is likely due to the reduced rate of change (spatially) of clutter in a suburban or commercial environment as compared to an urban environment.

- *Calibration Density* – increasing the calibration density from 1 – 3 passes again improved system accuracy. In this case, the improvement was slightly less pronounced than observed in Oakland, and appeared to have less effect on the 95th percentile performance.
- *MAHO Averaging Time* – preprocessing of the MAHO data by time-averaging the raw samples improved performance with approximately the same relative performance improvement as observed in Oakland testing.
- *MAHO Parameters* – as with the Oakland testing, no significant performance differences were observed for changes in antenna polarization or for changes in the specific handset under test. The stationary and mobile testing is currently in progress.

4 CONCLUSIONS

In this report, a detailed analysis of the Mobile-Assisted Network Location System (MNLS) performance has been presented. Both theoretical (model-based) and empirical field test performance analyses were presented.

The theoretical analysis utilized standard propagation models and was developed for both ideal and actual carrier market conditions. These models included the log-normal shadowing model and a CRC-based model. The CRC model was computed for two TDMA cellular markets including Oakland, CA and San Ramon, CA, representing an urban and suburban environment, respectively. For both markets, the models incorporated detailed carrier network data (such as cell site locations, antenna models, etc.) as well as terrain and clutter data. Both the log-normal and CRC models predicted that an MNLS system based on LPM technology would be capable of achieving performance better than 250m for 67% of the location fixes and better than 750m for 95% of the cases, under nominal operating conditions. A variety of special test cases were presented which revealed the performance impact of variations in specific MNLS and MAHO data parameters. The strongest parameter influences were observed for the MAHO time averaging interval (pre-processing of the MAHO data), the pairwise power difference standard deviation, and the number of channels in the MAHO neighbor list.

Empirical field test performance results were then presented for MNLS testing conducted in the San Ramon and Oakland, CA test regions. Performance was evaluated for the identical test regions as were modeled and described in the theoretical analysis, to facilitate comparison and establish the validity of the propagation models. MAHO data measurements were collected using two Ericsson TEMS Investigation TDMA 800/1900 air interface test tools and three TDMA handsets. A set of predetermined drive routes and stationary points were collected to provide comprehensive coverage and representative measurements of the conditions and operating environments expected within the designated test areas. Routes were typically repeated 4-6 times while systematically varying such parameters as the handset model, mobile speeds, antenna polarization, and time of day. A total of 390,362 MAHO data measurements were collected in Oakland, CA and 264,262 samples collected in the San Ramon, CA test region.

The statistical fluctuations of the MAHO data measurements were characterized in terms of the Absolute Power Metric (APM) and Pairwise Power Difference Metric (PPDM) for the complete data sets collected in each markets. The average standard deviation of the absolute power fluctuations within a 50m bin was found to be 9.66dB and 9.17dB for the Oakland and San Ramon markets,

respectively. Similarly, the fluctuations of the pairwise measurements were found to be significantly more robust and less variable, exhibiting values of 4.36dB and 4.21dB for the Oakland and San Ramon markets, respectively.

The overall MNLS performance achieved in both markets was in strong agreement with that which was predicted by the CRC model simulations. In the Oakland field test, the system achieved an overall MNLS accuracy of 183m for 67% of the location fixes, and 629m for 95% of the cases. For the San Ramon test region, the MNLS system achieved an overall accuracy of 214m for 67% of the location fixes, and 544m for 95% of the cases. The influence of variations in key MNLS system and MAHO data parameters were isolated and evaluated, revealing trends similar to those predicted by the performance modeling and simulation analysis. In particular, variations in the handset model and handset orientation were found to have little impact on MNLS performance.